

TITLE

Scalability of the Muscular Action in a Parametric 3D Model of the Index Finger

ABREVIATED TITLE

Muscular Action Scalability in a Finger Model

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Abstract

A method for scaling the muscle action is proposed and used to achieve a 3D inverse dynamic model of the human finger with all its components scalable. This method is based on scaling the *PCSA* (physiological cross-sectional area) in a Hill muscle model. Different anthropometric parameters and maximal grip force data have been measured and their correlations have been analysed and used for scaling the *PCSA* of each muscle. A linear relationship between the normalised *PCSA* and the product of the length and breadth of the hand has been finally used for scaling, with a slope of 0.01315 cm^{-2} , with the length and breadth of the hand expressed in centimetres. The parametric muscle model has been included in a parametric finger model previously developed by the authors, and it has been validated reproducing the results of an experiment in which subjects from different population groups exerted maximal voluntary forces with their index finger in a controlled posture.

Key terms

maximal force prediction

1. Introduction

Mathematical models of the hand are used to study different aspects of hand behaviour.^{1,3,6,8,10-13,15,16} For some purposes it is important to represent different population groups and percentiles, e.g., to aid therapists in the selection of the optimal handle diameter of personalised assistive devices for disabled people.

Previously,¹¹ the authors proposed a scalable 3D inverse dynamic model of the fingers based on data from literature, using the hand length and breadth (*HL* and *HB*) as scaling parameters. Scalability of rotation axes location was achieved using the work of Buchholz,⁴ tendon action scalability by adapting the model proposed by An,¹ and ligament action scalability by adapting the geometric model presented by Pagowski.⁹

In the absence of data from literature with regard to modelling differences in the muscular power of hands from different population groups, the authors considered a simple model for scalability in previous works,^{11,12} using the same *HL* and *HB* parameters used for scaling the rest of the model components. In this work, an improved model is presented and experimentally validated once integrated into a completely scalable 3D finger model.

2. Material and methods

Firstly, a scalable model of the muscular action based on the Hill muscle model is proposed. A specific experiment is designed in order to propose that model. Finally, its validity to predict maximal forces is investigated by incorporating this muscle model into the previously developed 3D inverse dynamic finger model.¹⁰⁻¹² A minimum number of parameters was used in the finger model: *HB* and *HL*. Its scalability was achieved as explained above, except for muscular action which we now go on to present.

2.1. Scalability of the muscular action

The muscle model considered had been previously presented,¹⁰ and consisted of three elements: a contractile element (CE), which is the basic component that generates force, a parallel elastic element (PEE), which is responsible for the passive force exerted by the muscle when it is stretched, and a series elastic element (SEE), the muscle tendon unit which has been considered inextensible. The force delivered by a muscle for a given posture can be written as:¹⁰

$$F = PCSA \cdot S_{\max} \cdot \left(\alpha \cdot F_l^{CE} \cdot F_v^{CE} + F_l^{PEE} \right) \quad (1)$$

where PCSA is the muscle physiological cross-sectional area, S_{\max} is the maximum stress the muscle can bear, which has been considered to be the same for each muscle,² α is the muscle activation level, F_l^{CE} and F_v^{CE} are the CE non-dimensional force-length and force-velocity relationships, and F_l^{PEE} is the PEE force-length relationship (see previous work¹⁶ for more details).

According to this model, the force delivered by a muscle for a given posture is proportional to its PCSA. To scale the muscular action, a scalability factor for the PCSA of each muscle should be considered. Holzbaur⁷ measured the muscle volume of upper limb muscles, observing that all muscles scaled by approximately the same ratio for each subject. Based on this observation, we propose a model that considers the same factor of scalability for the PCSA of all the muscles involved.

In the absence of data from literature, the previously presented finger model¹¹ considered the simple proposal of scaling the PCSA from a reference value measured for a given HL_{ref} and HB_{ref} in which a linear relationship with $HL \cdot HB$ was considered as both quantities have surface units:

$$PCSA(HL, HB) = PCSA(HL_{ref}, HB_{ref}) \cdot \frac{HL \cdot HB}{HL_{ref} \cdot HB_{ref}} \quad (2)$$

Significant errors occur with this model, when the hand size strays from the reference one. With this model, errors in the maximal force estimation are around 35% in some cases (see further on for details).

The next section presents the improvement of this model by means of a specific parameterisation study.

2.2. PCSA parameterisation study

An appropriate *PCSA* parameterisation in terms of hand dimensions, preferably *HB* and *HL*, was sought. An indirect estimation was made with data of maximal grip force (MGF) from many subjects.

MGF and anthropometric data of the hand and forearm were measured from a total of 106 subjects (55 males, 51 females, 27 ± 7 SD yr) with no history of permanent hand injury or dysfunction. The subjects exerted the MGF force with their predominant hand over a Biometrics© G100 dynamometer with a grasp distance that was adjusted in relation to the maximum grip diameter (MGD) of each subject to achieve a similar grasping posture for all subjects (Fig.1). Table 1 shows the three grasping distances and the number of subjects who used them. Two force measurements were conducted with a rest period of at least one minute between the two. The mean force of the maximum forces registered at each trial was used.

----- Insert Figure 1 about here -----

----- Insert Table 1 about here -----

Ten anthropometric dimensions were collected for all subjects in a standard way (Fig. 2): hand length (1), palm length (2), hand breadth (metacarpal) (3), hand breadth across thumb (4), maximum grip diameter (5), maximum spread (6), wrist breadth (7), wrist thickness (8), wrist circumference (9) and forearm circumference (10).

----- Insert Figure 2 about here -----

According to Valero-Cuevas,¹⁴ individual muscle forces are approximately linearly proportional to the magnitude of the external force. As a common scaling factor for all the *PCSA* of muscles is sought, it could be obtained from the scaling factor for the MGF. The correlation of the MGF with the anthropometric parameters and combinations of the best correlated ones was analysed. Once the anthropometric parameter(s) for scaling had been selected, the linear regression for the normalised MGF measured vs. this anthropometric parameter(s) was obtained. Furthermore, the slope from this regression was considered to be the same as the slope of the linear relationship for scaling the normalised *PCSA*.

2.3. Model validation

Twenty students (10 males, 10 females) were selected according to their hand sizes in order to obtain a representative sample (mean and standard deviation for *HL* and *HB* were 176 (10) mm and 79 (7) mm, respectively).

A special device was used to measure the maximal index finger force exerted in a controlled posture, with the same wrist posture for all participants, and the posture of the index finger visually controlled with a template so that it was similar among subjects (Fig. 3). A lateral photograph was taken to check this posture further. The subject was asked to increase the force until the maximal force and maintain it for approximately 3-4 seconds. After a rest period of several minutes, the whole process was repeated twice with a rest period in between. The mean force and posture of the three repetitions were used for each subject. Postures were checked to be the same for each subject in the three repetitions (SD less than 10°) using the technique defined in the work by Vergara.¹⁷

----- Insert Figure 3 about here -----

The mean posture and hand size for each subject were inputted to the finger model to predict the force. The forces predicted with this improved model and the original one were compared with the mean measured forces.

3. Results and discussion

3.1. Results from the PCSA parameterisation study

Table 2 shows the mean and standard deviation of the different anthropometric parameters considered and their correlations (Pearson correlation *r* coefficient) with the MGF measured. All correlations were statistically significant ($p < 0.01$). The best correlations for independent measurements were observed for *HB*, hand breadth across the thumb and forearm circumference.

----- Insert Table 2 about here -----

By taking into account that the PCSA is a surface, a parameter with surface units was sought for scaling. Table 2 shows also the correlation of the products of lengths and breadths and of the square of circumferences. Similar correlations were observed. The best one was found for the product of the palm length (PL) and HB slightly better than for the product of HL and HB . As a parameterisation in terms of HB and HL is preferred, this second one was used for the parameterisation. The linear regression obtained was:

$$MGF = -359.69 + 5.0855 \cdot (HB \cdot HL), \quad (3)$$

where HB and HL were expressed in cm and MGF in N.

Equation 3 yields an MGF of 381.57 N for the mean values of HL and HB ($\overline{HL} = 18.22$ cm, $\overline{HB} = 8.00$ cm). This force was selected to normalise the measured MGF:

$$Normalized\ MGF = -0.9427 + 0.01333 \cdot (HB \cdot HL). \quad (4)$$

The slope from Eq. (4) was considered to be the same as the slope for the linear relationship between the normalised PCSA and the product $HB \cdot HL$:

$$\frac{PCSA(HL, HB)}{PCSA(\overline{HL}, \overline{HB})} = 1 + 0.01333 \cdot (HB \cdot HL - \overline{HB} \cdot \overline{HL}) \quad (5)$$

It is clear, however, that muscular power also depends on the subjects' physical conditions, age, gender, etc. A more refined muscular model could include a correcting factor to account for these parameters.

3.2. Results from model validation

The mean posture and hand size for the subjects considered, used as input to the finger model, are presented in Table 3. Maximal force data estimated by the original model and the improved one for each subject, as well as the experimentally measured data, are presented in Fig. 4.

----- Insert Figure 4 about here -----

----- Insert Table 3 about here -----

Both models predict an increase of maximal force with the product $HB \cdot HL$ as well as the experimental measurements predict. As a consequence of the differences in the subjects' postures and individual factors (physical conditions, age or gender), this increase is not linear. The pattern obtained from the predictions with both models is similar to that measured experimentally, which means that the finger model properly reproduces the effect of the change of posture between subjects. Estimations from both models match the experimental values better as the hand size comes close to the 50th percentile.

The results of the new scalable model show an important improvement of the predictions in relation to the original model. The mean value of the absolute errors (absolute difference from experimental to model prediction) is smaller for the improved model (3.78N) than for the original one (5.65N). Some specific errors were expected, such as a 50% overestimation for subject 8 because the MGF measured with the Biometrics© dynamometer with this subject was 149% lower than that expected from Eq. (3). In order to avoid the effect of a specific subject's individual characteristics on the model errors, the experimental data have been lumped into five equidistant groups in terms of $HB \cdot HL$. The mean of the experimentally measured maximal forces for each group, as well as the estimations for each group with the averaged data as inputs (HB, HL and posture), are presented in Fig. 5. It can be more clearly observed that the improved model provides a better match than the old one. Again, absolute errors are smaller as the hand size nears the 50th percentile. Both the original and improved models underpredict force for large hands and overpredict force for small hands, but nonetheless the improved one presents smaller differences in their predictions. Maximum differences with the experimental measurements for extreme hand sizes are lower than 20% for the new model compared to more than 35% for the old model.

----- Insert Figure 5 about here -----

In the context of the present study, an error of 20% is considered reasonable if we take into account that the usual human force measurement presents a considerable scattering⁵ due to the different parameters that can affect the measurement, such as fatigue, measurement method, registration of maximum/mean, time that the force was endured, etc., apart from the individual parameters.

The model obtained is acceptable as a first approximation to the scalability of the muscular action in the index finger, and covers a wide range of percentile groups. The scalability of the model based only on two anthropometric measurements is practical but should be considered only as a first approximation: gender, age, physical conditions or body mass index, among other factors, could affect the accuracy of the model. Further research is needed to improve prediction of the model for extreme hand sizes.

Conclusions

A simple model has been presented to consider the scalability of the muscular action in a biomechanical model of the hand and has been validated for the index finger. This model is based on a Hill muscle model and is an improvement over a previous one which scales the *PCSA* of the muscles by means of a linear function in relation to the product of *HB* and *HL*. The coefficients of this function have been obtained from measurements taken with a dynamometer by adjusting the grasping size to the hand size of each subject from a group of 106 subjects. The new muscle model has been validated using data of a pinch experiment with 20 subjects. The predictions of the 3D inverse dynamic finger model incorporating the new muscle model are better than those from the old one since they present an error of less than 20% in relation to the experimental measurements.

Acknowledgements

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Tables

Table 1. Grasping distance and number of subjects that used each adjustable position of the dynamometer

	Position 1	Position 2	Position 3
Grasping distance (mm)	47	60	73
Females	20	31	0
Males	3	49	3

Table 2. Mean and standard deviation of the anthropometric parameters and their correlations with the mean MGF measured with the dynamometer

Parameter	Female	Male	Male & Female	Correlation
	Mean (SD)	Mean (SD)	Mean (SD)	with force (male & female)
<i>HL</i> (mm)	173.3 (7.6)	190.4 (8.5)	182.2 (11.8)	0.740
<i>PL</i> (mm)	100.1 (4.8)	111.0 (5.4)	105.7 (7.5)	0.763
Hand breadth across thumb (mm)	88.2 (4.7)	100.2 (4.8)	94.4 (7.7)	0.832
<i>HB</i> (mm)	74.6 (3.4)	84.9 (4.6)	80.0 (6.6)	0.848
Maximum grip diameter (mm)	46.1 (3.5)	50.3 (3.9)	48.2 (4.2)	0.584
Wrist breadth (mm)	51.8 (3.1)	58.8 (3.2)	55.3 (4.7)	0.788
Wrist thickness (mm)	36.8 (2.4)	42.1 (2.7)	39.6 (3.7)	0.738
Wrist circumference (mm)	147.6 (9.0)	169.4 (9.6)	158.9 (14.4)	0.784
Maximum spread (mm)	198.0 (12.0)	219.1 (12.3)	208.9 (16.1)	0.721
Forearm circumference (mm)	228.6 (17.6)	275.1 (16.7)	252.7 (28.9)	0.810
<i>HL</i> · <i>HB</i> (cm ²)	129.44 (10.30)	161.94 (14.41)	146.31 (20.58)	0.836
<i>PL</i> · <i>HB</i> (cm ²)	74.73 (5.91)	94.41 (8.60)	84.94 (12.34)	0.852
(Forearm circumference) ² (cm ²)	525.63 (88.00)	759.49 (93.74)	646.97 (148.29)	0.800
(Wrist circumference) ² (cm ²)	218.45 (27.05)	287.74 (32.61)	254.40 (45.89)	0.778
Wrist breath · Wrist thickness (cm ²)	19.08 (2.16)	24.77 (2.65)	22.03 (3.74)	0.796

Table 3. Mean postures and hand sizes of each subject participating in the validation experiment, and used as input to the model.

	HL	HB	MCP	PIP	DIP	Distal phalanx-
	(mm)	(mm)	flexion (°)	flexion (°)	flexion (°)	plate angle (°)
			Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Subject 1	161	69	14 (4)	35 (4)	20 (5)	48 (3)
Subject 2	166	70	35 (3)	22 (6)	9 (4)	39 (7)
Subject 3	164	72	15 (2)	48 (4)	15 (0)	54 (2)
Subject 4	162	74	22 (8)	32 (6)	31 (2)	57 (3)
Subject 5	170	72	17 (4)	34 (2)	17 (3)	46 (3)
Subject 6	167	74	25 (2)	44 (2)	12 (3)	54 (2)
Subject 7	175	73	22 (5)	41 (5)	19 (5)	55 (3)
Subject 8	176	76	26 (3)	39 (1)	17 (1)	53 (1)
Subject 9	174	79	23 (2)	32 (3)	31 (2)	57 (2)
Subject 10	177	78	17 (1)	35 (3)	11 (1)	37 (2)
Subject 11	179	78	19 (2)	36 (2)	18 (2)	51 (1)
Subject 12	170	84	26 (3)	39 (2)	26 (3)	55 (2)
Subject 13	183	82	16 (4)	42 (3)	29 (4)	59 (3)
Subject 14	178	85	11 (2)	40 (2)	16 (2)	49 (2)
Subject 15	185	83	14 (2)	32 (3)	14 (0)	41 (1)
Subject 16	182	85	23 (3)	35 (3)	15 (2)	44 (2)
Subject 17	191	86	21 (10)	32 (7)	21 (4)	51 (2)
Subject 18	183	92	17 (8)	31 (5)	11 (1)	39 (3)
Subject 19	195	91	29 (5)	28 (5)	16 (1)	42 (2)

Subjects have been ordered from lower to greater *HL*·*HB*. Data corresponding to one subject were discarded because his hands were very large (*HB* = 108 mm; *HL* = 230 mm). The postures of the three repetitions for all subjects were within 10° of SD variations in all cases, so no other datum was discarded.

Figure legends

Figure 1. Hand dynamometer with the three grasping adjustments used in the study. Subjects were asked to exert the maximal voluntary grip force with their predominant hand while maintaining a standardised posture: standing with the shoulder relaxed, the arm stretched alongside the body, and the wrist in a neutral posture of flexion and lateral deviation. Only three of the five discrete grasping positions of the dynamometer were used for grasping comfort. Grasping was adjusted to the position nearest to 1.35xMGD for each subject.

Figure 2. Eight of the ten anthropometric dimensions measured in the experiment: 1) hand length, 2) palm length, 3) hand breadth (metacarpal), 4) hand breadth across thumb, 5) maximum grip diameter, 6) maximum spread, 7) wrist breadth, 8) wrist thickness.

Figure 3. Photos taken of a large (a) and small (b) hand to control the finger posture before asking subjects to exert the maximal force. The device was calibrated to measure the compressive force exerted over the gripping area. The same wrist posture was adopted by all the participants: the forearm resting on a horizontal plane, the wrist in a neutral posture and the hand resting on the plane with all fingers grouped except the index finger. The posture of the index finger was visually controlled so that it was similar among subjects: metacarpophalangeal (MCP) and proximal and distal interphalangeal (PIP and DIP) joints slightly flexed, and the MCP joint in neutral abduction. To achieve this posture, the distance of the hand and height of the horizontal plane were adjusted for each subject.

Figure 4. Mean maximal forces experimentally measured for each subject participating in the validation experiment and estimated by the original and improved models.

Figure 5. Mean maximal forces experimentally measured and estimated by the original and improved models. The data have been lumped into five equidistant groups in terms of HB·HL.

Figures

Figure 1.

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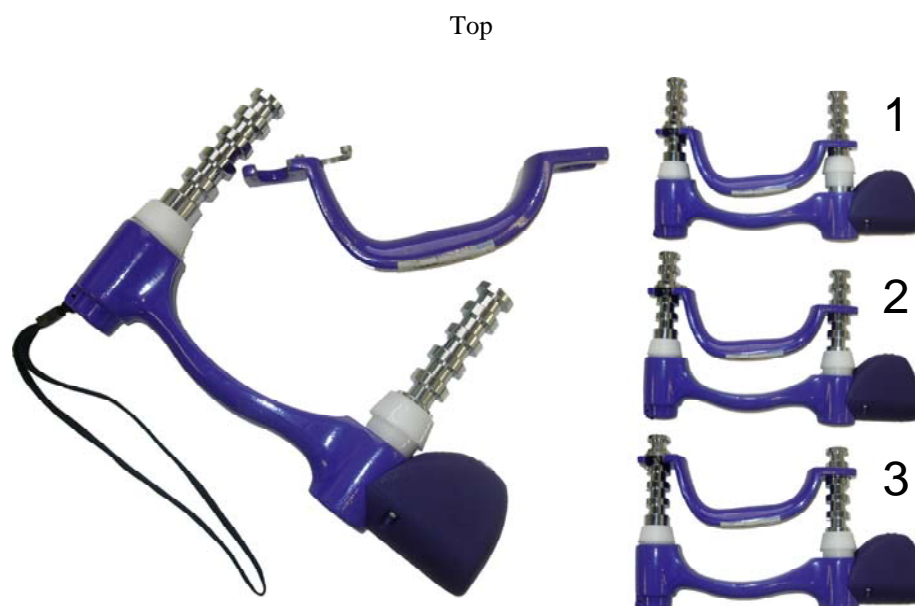


Figure 2.

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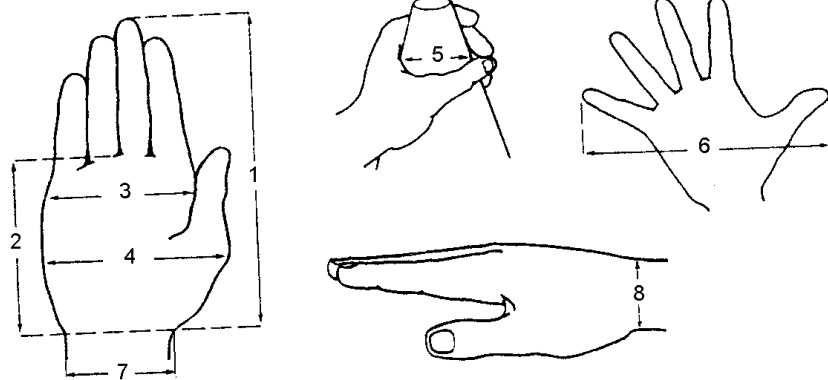


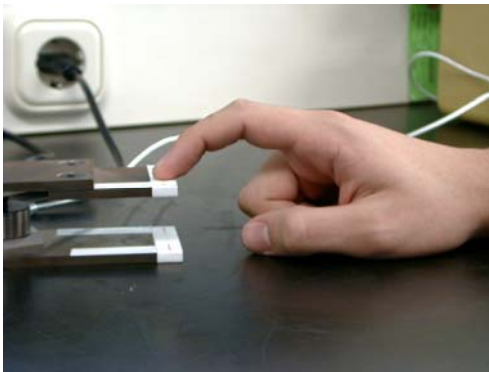
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(a)



(b)



Figure 4.

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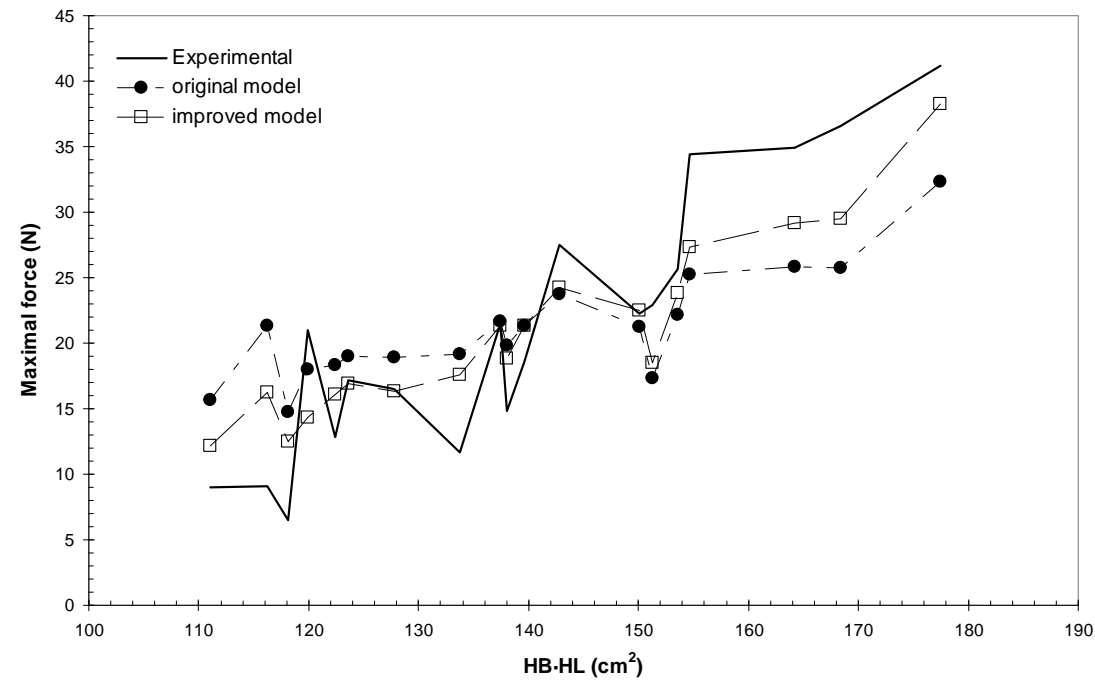


Figure 5.

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